Short Course on Experimental Dynamic Substructuring

Module #1: Introduction

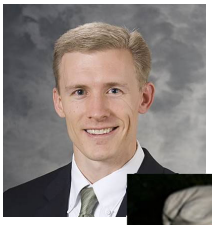
Matthew S. Allen
Professor, Engineering Physics Dept, University of Wisconsin-Madison
Randall L. Mayes
Distinguished Member of Technical Staff, Sandia National Labs.
Paolo Tiso
Senior Scientist, Dept. of Mechanical and Process Eng., ETH Zürich

Short Course Notes For:
February 8, 2020, IMAC, Houston, TX, USA

1

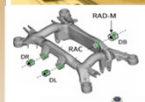
About the Instructors

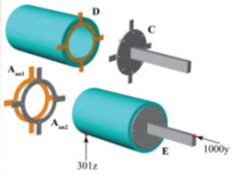
- **Instructor**
  Prof. Matt Allen, Professor
  Department of Engineering Physics,
  University of Wisconsin-Madison
  1500 Engineering Drive, 525 ERB, Madison, WI 53706
  msallen@engr.wisc.edu
  608.890.1619
  http://sd.engr.wisc.edu
- **Instructor:**
  Randall L. Mayes, Distinguished Member of Technical Staff
  Sandia National Laboratories, Albuquerque, NM.
  rlmayes@sandia.gov
  505.844.5324
- **Instructor:**
  Dr. Paolo Tiso,
  ETH Zürich, Dept. of Mechanical and Process Eng.
  Leonhardstrasse 21
  8092 Zürich, Switzerland
  ptiso@ethz.ch
  +41 44 632 36 41
  http://georgehaller.com/about/members/tiso/index.html



2

Outline / Schedule




- 9:00 - **Mod01:** Introduction/Motivation - **Matt**
- 9:30 - **Mod02**: General Theory - **Paolo**
  - 10:30 (15 min) Break
- 10:45 - **Mod03**: Simple Exercises (Matlab/Octave) - **Matt**
- 11:30 - **Mod04**: General Theory II - **Paolo**
  - 12:30-1:30 PM - Lunch Break
- 1:30 - **Mod05**: Measurement Considerations - **Randy**
- 2:15 - **Mod06**: Transmission Simulator - **Matt**
  - 3:15 (15 min) Break
- 3:30 - **Mod07a**: Est. Fixed-Interface Modes - **Matt**
- 4:00 - **Mod07b**: Payload and Component Simulations using Craig Bampton Form Modal Models - **Randy**
- 4:30 - **Mod08**: Geometrically Nonlinear Systems - **Paolo**
- 5:00 - **Mod09**: Closing Remarks
- [Appendix] - **Mod10**: Hands on Exercise: Guitar - **Matt**

3

Informal Survey

Have you:

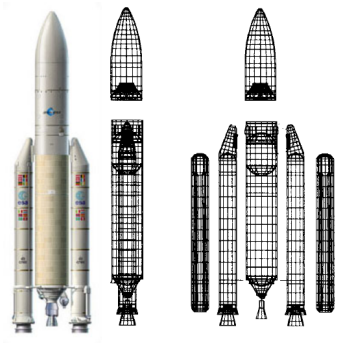
- Had an undergraduate-level class on vibrations?
- Had a graduate-level class on vibrations?
- Had a graduate-level class on finite element analysis? Experience with FEA?
- Ever performed a modal test? Regularly?

- Approach for this short course
  - 80% Lecture , 20% Guided exploration
  - Files needed for the examples can be obtained at:
    - http://substructure.engr.wisc.edu/ in the “Tutorials” section:
    - http://substructure.engr.wisc.edu/substwiki/index.php/Tutorials
- Assessment :
  - You will be asked to complete a short questionnaire within a few days of the short course to help the instructors to evaluate its effectiveness.

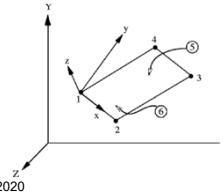
4

What is Substructuring?

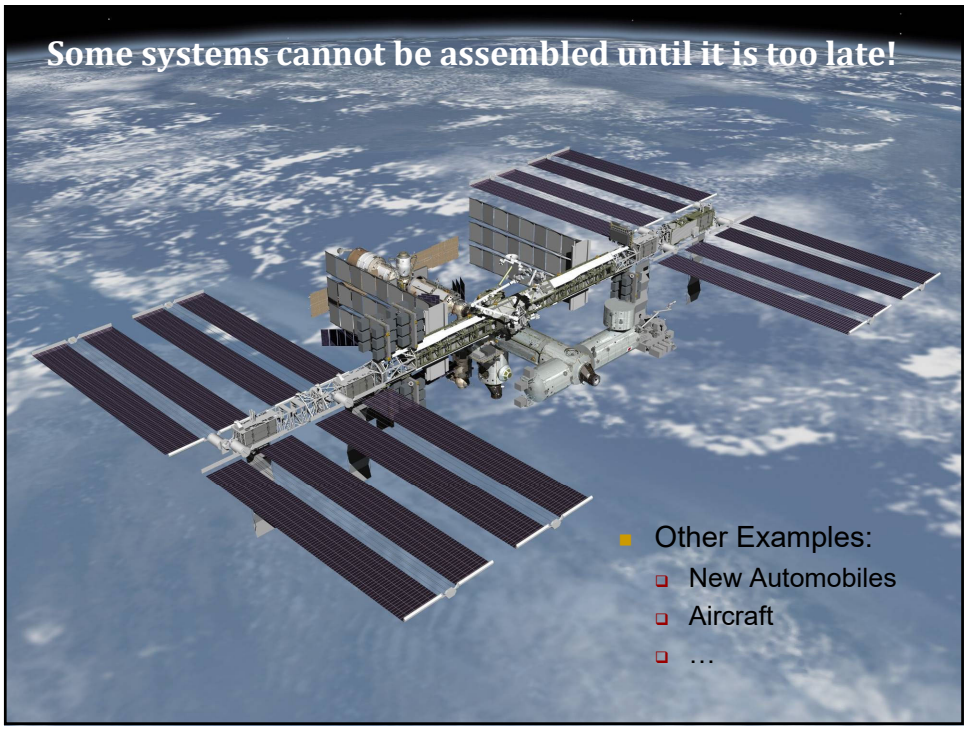
- Substructuring is a process whereby individual components of a structure are analyzed or tested separately and then combined to predict the response of the built-up structure.
  - Reduced Order Modeling: create an approximation to a model to reduce the computational burden
- Analytical substructuring forms the basis of the Finite Element Method, and related techniques, such as the Craig-Bampton method, have been key components of structural analysis for over 40 years.
- **Experimental/Analytical Substructuring** is a far less common variant where a model for one or more subcomponents is derived experimentally.



Ariane 5 Launch Vehicle (ESA) and diagram depicting potential substructures

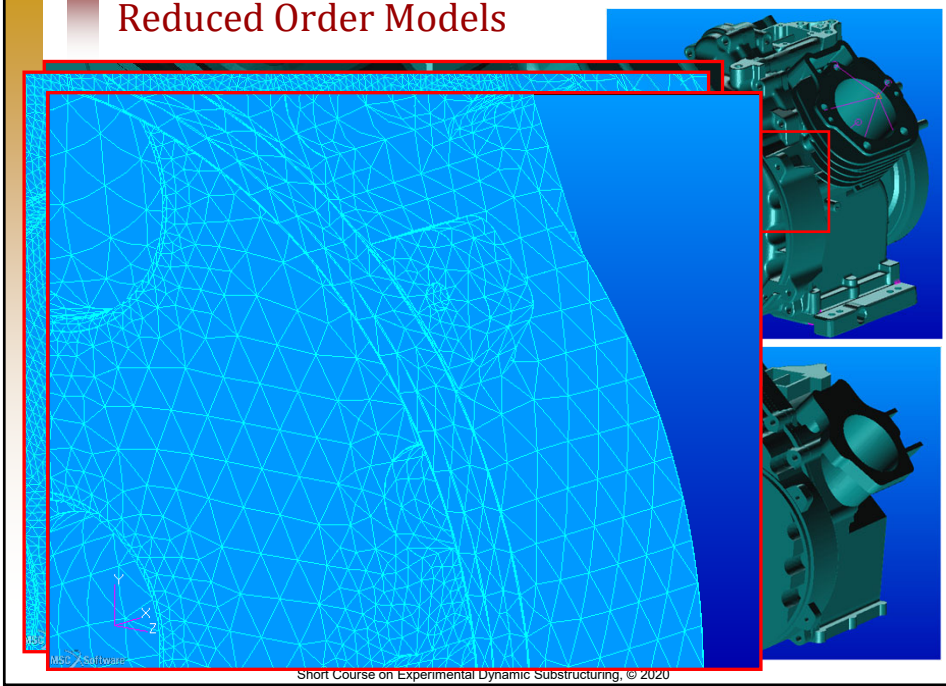


5



6

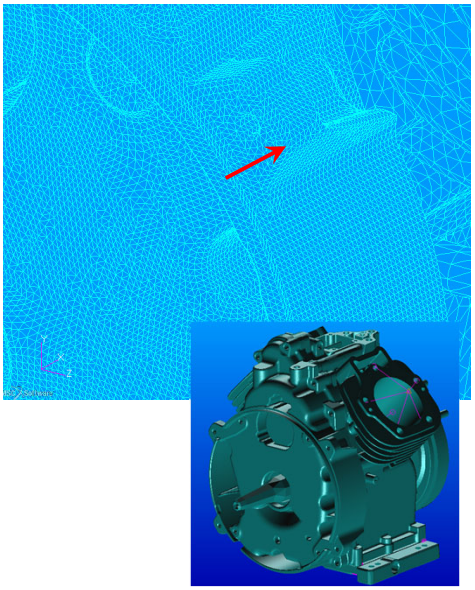
Reduced Order Models



7

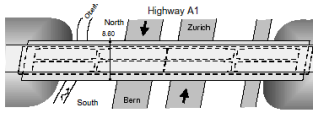
Basics of Substructuring / Reduced Order Modeling

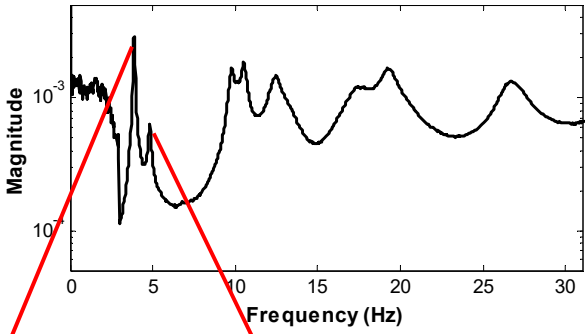
- A complete FEA model allows for arbitrary motion of any node of the structure.
- A substructure or reduced order model can be more efficient by capturing only those motions that are likely in the application of interest.
- This is especially relevant to structural dynamics, where the deformations observed are often the net effect of only a few vibration modes.

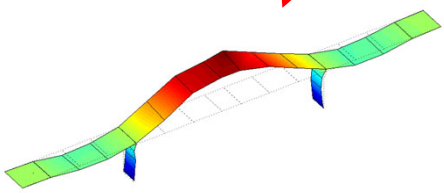


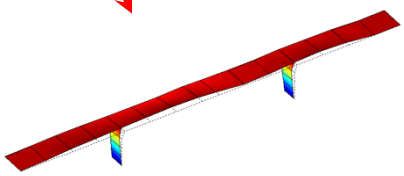
8

Example – Swiss Highway Bridge



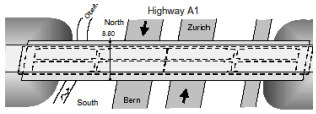


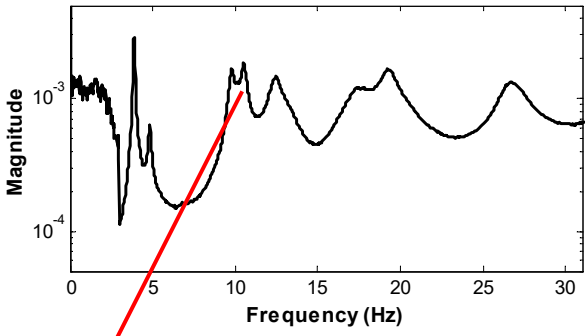




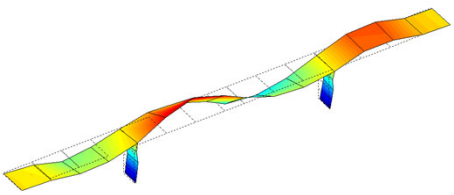
9

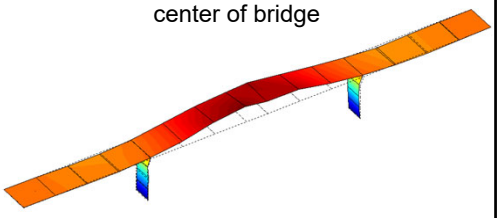
Example – Swiss Highway Bridge





Response to impulse applied to center of bridge

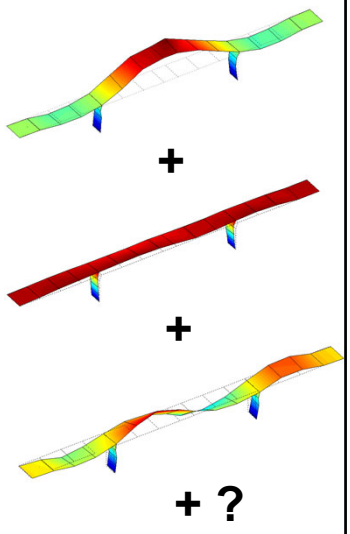




10

How many modes do we need to predict the modes of the bridge after changing mass or stiffness?

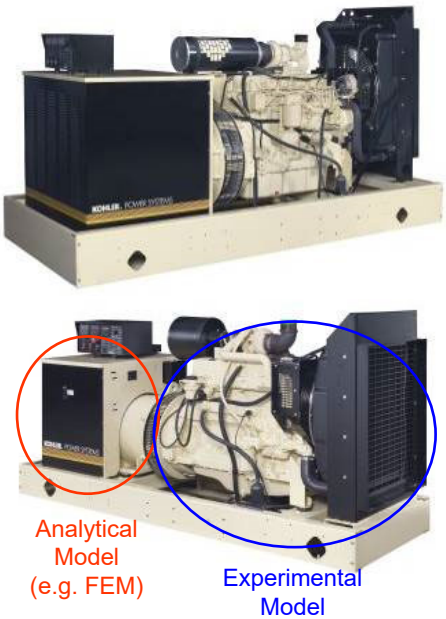
- We'll see that vibration modes alone don't form an ideal basis for substructuring – some important components are missing!
- The various substructuring methods take different approaches to address this.
- Understanding what these components are leads to important insights regarding which properties of each subcomponent affect the assembled response.



11

Experimental – Analytical Substructuring

- We are often tasked with analyzing systems where one or more components are very difficult to model analytically.
  - Intricate geometry
  - Drawings proprietary or unavailable
  - Unknown material properties
  - Bolted joints with complicated stick-slip behavior
  - …
- These components can potentially be replaced with an experimentally derived model.



12

Experimental Substructuring CHALLENGES

- Approach is limited to motions that can be measured accurately.
  - Free-free boundary conditions:
    - Easy to reproduce experimentally
    - But, free-free modes are missing important ingredients that are needed for accurate substructuring.
  - Fixed interface modes (i.e. Hurty/Craig-Bampton Method)
    - Difficult or impossible to realize experimentally!
- Measurements are subject to noise / errors.
  - How do we design tests to reduce errors?
  - Can an adequate model be created in the presence of inevitable measurement errors?
  - Substructure models require the rotation at the connection point, which is challenging to measure reliably!

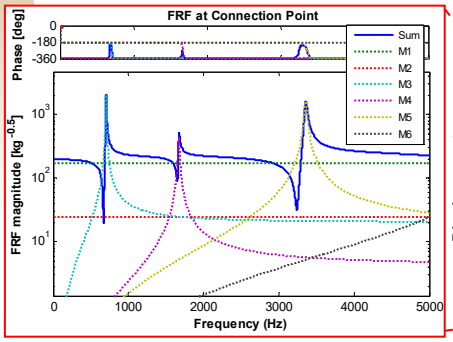
Free-free boundary conditions

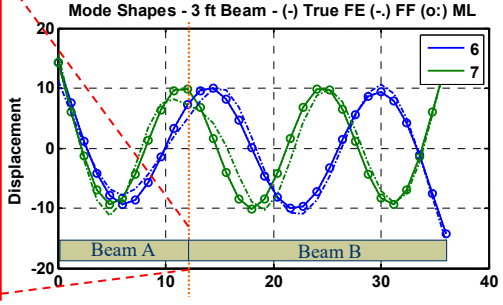
Fixed-Interface?

13

Inter-relationships between FBS and MS

- Discussion so far focused on Modal Substructuring
- Frequency Based Substructuring:
  - An alternative where the Frequency Response Functions (FRFs) of each component are combined to predict the FRFs of the assembly.
- These have different advantages and disadvantages and give different yet complimentary views on the accuracy required!





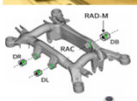
14

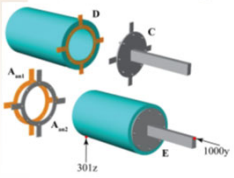
Mathematics Notation used in this Short Course

- This course uses the following mathematical notation (as much as possible) although some deviations will be necessary:
  - Scalar variables italic: $x, y, z, \ldots$
  - Vectors and matrices bold upright: $\mathbf{x}, \mathbf{y}, \mathbf{M}, \mathbf{K}, \ldots$
  - When possible lower case for time-varying vectors and upper case for vectors that are functions of frequency: $\mathrm{x}(t), \mathrm{X}(\omega)$
- **Our goal is for you to learn and gain new skills. Please feel free to ask questions at any time!**

15

Outline / Schedule





- 9:00 - **Mod01:** Introduction/Motivation - **Matt**
- 9:30 - **Mod02**: General Theory - **Paolo**
  - 10:30 (15 min) Break
- 10:45 - **Mod03**: Simple Exercises (Matlab/Octave) - **Matt**
- 11:30 - **Mod04**: General Theory II - **Paolo**
  - 12:30-1:30 PM - Lunch Break
- 1:30 - **Mod05**: Measurement Considerations - **Randy**
- 2:15 - **Mod06**: Transmission Simulator - **Matt**
  - 3:15 (15 min) Break
- 3:30 - **Mod07a**: Est. Fixed-Interface Modes - **Matt**
- 4:00 - **Mod07b**: Payload and Component Simulations using Craig Bampton Form Modal Models - **Randy**
- 4:30 - **Mod08**: Geometrically Nonlinear Systems - **Paolo**
- 5:00 - **Mod09**: Closing Remarks
- [Appendix] - **Mod10**: Hands on Exercise: Guitar - **Matt**

16